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Embodied energy assessment for Macao's external trade

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ABSTRACT

As a typical heterotrophic city, Macao's economic boom is fueled by external trade, which provides Macao with not only direct energy products in forms of oil, gas and electricity, but also indirect energy embodied in other imports. However, the prevalent studies on Macao's energy issues are confined to direct energy inputs. Based on the most recent trade statistics and embodied energy intensity databases, a comprehensive assessment of energy embodied in Macao's external trade after its sovereignty handover is performed. The results show that Macao's embodied energy consumption is over 2 times as that of direct energy consumption. The net embodied energy transfer via external trade from other regions to Macao increased from 6.31E+7 GJ in 2000 to 8.75E+7 GJ in 2011, while the embodied energy intensity dropped sharply from 1.02E+04 GJ/ million USD to 2.40E+3 GJ/million USD in the same period. Non-energy-products and services rather than energy products play the key role in energy transfer, indicating that indirect energy dominates Macao's embodied energy consumption. The largest energy imbalance happens between Macao and mainland China. Given the nature of Macao's economy and escalating socio-economic development, it is suggested that the invisible but dominant indirect energy consumption by Macao should be addressed by decision makers and included in future development strategies.

Contents

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1. Introduction

Macao, one of the special administrative regions of China, is a diverse, highly impacted and rapidly changing region. From 2000 to 2011, the population of Macao grew from 437,900 to 557,400, and the area of land expanded from 25.4 km^2 in 2000 to 29.9 km^2 in 2011 by reclamation [1–12]. With population growth outpacing land growth, the population density of Macao increased from 17,240 persons/Km^2 to 18,640 persons/km^2, making Macao the world's most highly dense region. At the same time, Macao has become one of the richest regions in Asia; with its GDP increasing from 6.21 billion USD in 2000 to 36.43 billion USD in 2011 and per capita GDP increasing from 15,169 USD to 66,311 USD. The prosperous economy is mainly driven by Macao's external trade (shown in Fig. 1). Especially, according to the statistics, the value of service trade is equal to over four fifths of Macao's GDP in 2011. The service trade is dominated by service export, which lies in Macao's unique culture and service industry. As a former colony of the Portuguese, the integration of Chinese and Portuguese cultures and religious traditions for more than four centuries has left Macao with a diverse culture characterized as an inimitable collection of historic buildings, holidays, festivals and events [13]. In the most recent decade, attracted by Macao's diverse culture and instinctive gaming industry, millions of tourists rush to Macao and contribute significantly to Macao's growing wealth.

As energy is essential for the development and survival of human society, Macao inevitably consumes massive energy associated with trade to satisfy the growing economy, population, tourists and the rising living standards of local residents. According to the statistics [14–25], the total energy used by Macao increased from 2.49E+7 GJ in 2000 to 3.20E+7 GJ in 2011, with a growth rate of about 30%. In the context of the ongoing urbanization, more significant growth of energy use is expected to take place in Macao. The growing energy demand has posed an unprecedented challenge for Macao because Macao is a typical heterotrophic city which has no indigenous fossil energy resources. Consequently, Macao shows a great dependence on trade and all the energy products used by Macao are all imported from other regions.[1]

Now Macao's energy issues have attracted more and more attention in the academic field in recent years, with regard to their distinctive features. Based on mathematical models, Lai et al. [26] identify that temperature, population, the number of tourists, hotel room occupancy and days per month are the five factors that could be used to characterize Macao's monthly electricity consumption. Later, the vector error correction model has been applied by Lai et al. [27] to reveal the relationship between Macao's electricity consumption and economic growth. On the basis of Lai et al.'s work, To et al. [28] evaluate Macao's electricity consumption and its environmental impact by accounting its greenhouse gas emissions. Li and Chen [29] carry out a comprehensive review on Macao's total direct energy use, energy mix and sectoral energy structure during the period of 2000~2010. All these existing studies have contributed greatly to increasing knowledge on Macao's energy issues and provided insights for Macao's energy conservation strategies.

However, all the aforementioned studies on Macao are confined to the perspective of direct energy inputs. As a matter of fact, besides energy products, most of the necessities that sustain Macao's socio-economic development are reliant on external trade, due to its extremely limited natural resources. And all the products and services are directly or indirectly originated from energy use [30,31]. As for Macao, it not only directly imports the energy products like fuel, gas and electricity, but also exchanges indirect energy embodied in commodities and services with other regions. Therefore, external trade is a mean of transferring virtual energy resources between Macao and other places. When these goods or services are exchanged between Macao and various regions, embodied energy "flow" occurs. This can also be verified by Li et al. [32], which shows that Macao's consumption has caused the majority of its GHG emissions outside its territory through trade, implying that Macao has also induced a large amount of off-site energy consumption elsewhere. That is to say, there is a certain amount of energy that silently contributes to Macao residents' daily lives, businesses and industries. However, the role of indirect energy in Macao's energy issues has been ignored, in striking contrast to the focus on the direct energy input and consumption.

In contrast to direct energy input, embodied energy as a conception provides a complete perspective on energy analysis. Defined as the total (direct plus indirect) energy required in generating goods or services [33,34], embodied energy is applied to investigate indirect energy effects. Regarding the significant role of external trade in Macao's socio-economic development, embodied energy study on Macao can be performed to reveal the external trade's influence on Macao's local energy consumption. Therefore, the aim of this study is to comprehensively review the energy embodied in Macao's external trade, as an extension of conventional direct energy accounting as presented in Li and Chen [29].

The remainder of the paper is structured as follows. Section 2 describes and methodology and briefly introduces the data applied in this study. Section 3 summarizes the results of embodied energy induced by Macao from 2000 to 2011. In Section 4, highlights of this study are discussed. Finally, the conclusion is presented in Section 5.

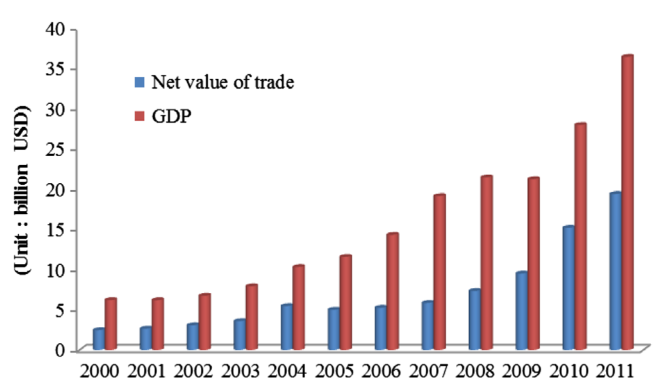


Fig. 1. Macao's GDP and net value of trade.
Data source: are derived from [1–12].

[1] Although Macao generates electricity locally, the fuels that local power plants use are all imported from other places.

2. Methodology and data sources

2.1. Overview of embodied energy accounting

Although a large number of studies on embodied energy analysis have been carried out, there is no uniform method to assess energy embedded in a product, due to the different understandings of scope, scale and type of energy embodied. In general, these studies can be roughly classified into two major groups according to their methodologies. One is on the basis of Life Cycle Analysis (also known as life cycle energy assessment, LCA), and the other is dependent on input–output analysis (IOA).

LCA is a technique which aims to assess energy inputs involved in all the stages of a product or service's life from cradle to grave [35,36]. For instance, under the framework of LCA, the energy inputs to a building are not only direct energy input during operation such as lighting, heating and ventilation, but also all energy inputs required by building materials such as cement, steel, services needed for the construction process, waste disposal or recycling. With the help of LCA, many studies on embodied energy accounting were carried out by different researchers. Examples include analysis on embodied energy in wetland technologies [37], wastewater treatments [38], various residential buildings in different countries [39,40], and calculation of embodied energy associated with socio-economic development [41,42]. These LCA-based literatures have contributed significantly to supporting policy makers to inform decisions by providing the detailed information for revealing the embodied energy effects assignable to products.

Nevertheless, despite the fact that LCA is a powerful tool for evaluating the embodied energy, there are some arguments and criticisms on LCA. A lack of consistency in the methods used to track energy during the product life cycle was found, because some inputs are inevitably neglected and truncated after several stages, due to the time-consuming and infinite trace process. Even worse, sometimes the tracing might fall into a loop [43,44].

IOA originated from Wassily Leontief's input–output model [45]. Compared with LCA, IOA can provide a panorama of energy flows of the entire system and consistent energy intensity data. Additionally, it is a solution to the truncation errors involved by LCA [46,47]. Since 1960s, the IOA was extended to describe the relationships between economies and environment [48]. Costanza [49] adapted this technique to explore the embodied energies required for production and pointed out the embodied energy has strong relationship with economic value. By virtue of the input–output table and expenditure data, Lenzen et al. [50] accounted energy requirements of Sydney households and found out the correlations between embodied energy requirement and household income, size, age, and degree of urbanity. Besides, the IOA has satisfied some investigators' needs to distinguish direct and indirect energy and their implications on energy policy, or analyze the relationship between embodied energy and the greenhouse gas emission [51,52]. Specifically, IOA has been widely used to analyze energy and carbon emissions flows embodied in international trade (e.g., [33,53–55]).

In recent years, based on the multi-scale input–output model, Chen and his co-workers have developed a method of systems accounting which is extensively employed to account for ecological endowments such as energy, water, greenhouse gas emissions of economies at different scales [44,56–63]. Also, integrated embodied energy intensity databases at different scales were constructed by applying systems accounting. At the city scale, Chen et al. [57] calculated the embodied energy intensity for the city of Beijing. At the national scale, a previous study carried out by Chen and Chen [56] compiled the embodied energy intensities for 135 economic sectors for China's economy. At the global scale, embodied energy intensities of 57 economic sectors in 112 countries and regions are presented in Refs [58] and [60].

However, due to the lack of input–output table, IOA cannot be directly employed to investigate Macao's embodied energy. Therefore, this study applies a compound top-down approach integrating the statistics data with embodied energy intensities at different scales, which are obtained by IOA. This method has successful applications in assessing greenhouse gas emissions and energy consumption of various systems (e.g., [29,32,44,58]) and is illustrated in detail in the following section.

2.2. Method

The energy embodied in external trade is obtained by multiplying the trade figures (import and export) and the corresponding energy intensity coefficients.

Embodied energy of imports (*EEI*) equals the sum of energy embodied in imported products (*EEIc*) and imported services (*EEIs*). Thus, *EEI* can be calculated as

$$EEI = EEIc + EEIs = \sum_{i}^{j}(I_{i,j} \times EI_{i,j}), \tag{1}$$

where $I_{i,j}$ means import product or service i from source j, and $EI_{i,j}$ is the corresponding embodied energy intensity. For instance, to calculate the embodied energy of electricity imported from mainland China, the embodied energy intensity of Sector *Production and supply of electricity* within mainland China is selected. It should be noted that *EEIc* is divided into two parts: one is embodied energy of imported products and the other is embodied energy of other commodities.

Similarly, embodied energy of exports (*EEE*) can also be obtained by embodied in exported products (*EEIc*) and exported services (*EEIs*)

$$EEE = EEEc + EEEs = \sum_{k}(E_k \times EI_k), \tag{2}$$

where E_k means product or service k exported to other places, EI_k is product or service k's embodied energy intensity. As there has been no input–output statistics in Macao for an energy input–output analysis, we have to resort to the global mean intensities [56,60] for a reasonable estimation of the energy embodied in the export.

With the results of *EEI* and *EEE*, embodied energy consumption *EEC* is equal to *EEI* minus *EEE*:

$$EEC = EEI - EEE \tag{3}$$

The approach applied in the present work reflects the energy avoided by external trade. Time period of Macao's post-colony is a particular phase for its development and deserves special look, therefore 2000~2011 is chosen as the time period concerned in this study.

2.3. Data sources

The relevant direct energy use and economic data are obtained or derived from the official statistical yearbooks issued by Macao Statistics and Census Service, such as *Macao Yearbook* [1–12] and *Balance of Energy* [14–25]. The detailed items of both imports and exports are separately listed in Table A1 and A2. In Table A1, item nos. 1–40 are imported commodities, nos. 41–47 are imported energy products, nos. 48–54 are imported services. In Table A2, item nos. 1–20 are exported commodities, nos. 21–26 are exported services.

The embodied energy intensity of each commodity as well as service is derived from the aforementioned databases, i.e., Chen and Zhang [64] and Chen [58]. These databases provide solid foundation for Macao's energy consumption and embodied energy calculation in this study. All prices are transformed into those of the base year, as the prices for each item can be obtained in detail in the statistics. And each of the original currency is transformed into MOP based on the currency exchange rates provided by the Macao's Yearbook.

3. Results

3.1. Energy embodied in commodity trade

3.1.1. Embodied energy of energy products consumed

Unlike the direct energy input, the embodied energy of energy products consumed by Macao experienced consistent growth. The total embodied energy of energy products increases from 4.24E+7 GJ in 2000 to 7.79E+7 GJ in 2011, with a growth rate of 83.46% (Fig. 2). Significant growth of energy embodied in electricity consumption can be witnessed after 2005 (Fig. A1). The main reason behind this is that Macao has increased the imports of electricity from mainland China by a large margin, which has a high embodied energy intensity. As opposed to electricity, the embodied energy in fuel oil which is mainly used to produce local electricity was reduced by a large amount in the same period accordingly. As the structure of direct energy input into each economic sector is unknown, consequently, it is impossible to calculate the embodied energy of energy products consumed by each sector.

3.1.2. Energy embodied in imported commodities (energy products excluded)

Appendix Table A3 summarizes the information on the trends of energy embodied in imports of commodities over 12 years. The total embodied energy in imports first increased from 6.01E+7 GJ in 2000 to 8.73E+7 GJ in 2005. Then the embodied energy experienced three consecutive years' decrease and fell to 3.97E+7 GJ in 2009 due to the worldwide financial crisis, in 2011 the value of embodied energy increased to 5.13E+7 GJ.

In 2000, Textile yarn, fabrics, made-up articles, n.e.s (means not elsewhere specified), and related products, articles of apparel and clothing accessories and electrical machinery, apparatus and appliances, n.e.s., and electrical parts thereof are the three biggest contributors to the imported embodied energy. Energy embodied in these three imports together is responsible for over four fifths of the total imported energy embodied in goods, while the three smallest imports (feeding stuff for animals (not including unmilled cereals), Metal products, n.e.s. and fixed vegetable fats and oils, crude, refined or fractionated) only take a share of less than 0.2%.

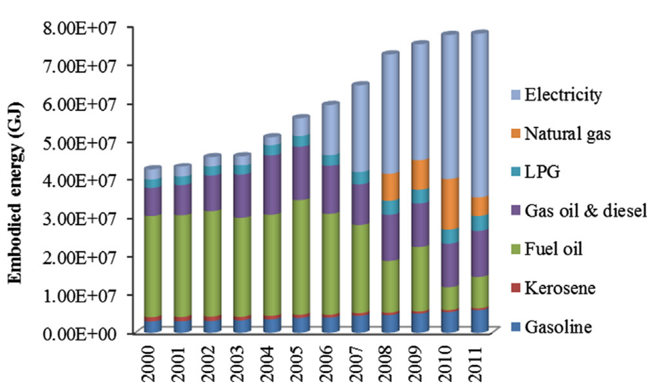


Fig. 2. Embodied energy of energy products consumed.

As the structure of imported commodities changes a lot after 2005, the biggest three contributors of energy embodied in imported commodities also change, which are telecommunications and sound recording and reproducing apparatus and equipment, iron and steel and beverages, respectively in 2011.

3.1.3. Energy embodied in exported commodities

With the fluctuation of exports value, the trend of energy embodied in exports also experienced a rise and fall. In 2000 the embodied energy of exports was 3.00E+7 GJ with a growth rate of about 40% energy embodied in exports reached pinnacle at 4.19E+7 GJ in 2004. However, since 2005, energy embodied in exports dropped off sharply. When it came to 2011, the embodied energy in exports was only equal to 14% of the maximum value in 2004. The decline of exported embodied energy mainly resulted from two factors. One is that since Macao has scarce land and natural resources, Macao's government decided to reduce the size of the traditional garment manufacturing industry [13], whose products are the primary contributors to Macao's exports. The other is that the World Trade Organization made the abolition of Macao's export quotas in the international garment trade effective in 2005. Greatly influenced by these two factors, the garment manufacturing industry inevitably fell into recession. Thus, the embodied energy in exports decreased along with the reduction of the garment related exports. Even though, in terms of the import structure, *Garments*, *Textile fabrics* and *Textile yarn and thread* exports are still the most important contributors of embodied energy in exports, together accounting for more than four fifths of the total in period concerned, as shown in Appendix Table A4.

3.1.4. Embodied energy of commodity trade flows

Presented in Fig. 3 are the embodied energy flows between Macao and its main commodity trade partners in 2000 and 2011. Apparently, mainland China maintains its position as the leading exporter of Macao's embodied energy in commodities. In the period concerned, Mainland China contributes the biggest share (more than 50%) of Macao's imported embodied energy in commodities. That is because half of Macao's fuels, most of its food and all of the imported electricity come from mainland China. As the second largest importing source, the embodied energy that Macao receives from Japan increased from 1.18E+7 GJ in 2000 to 2.20E+7 GJ. The majority of commodities imported from Japan are *Photographic apparatus*, *equipment and supplies and optical commodities*, *n.e.s.*; *clocks and watches* and *Essential oils and resinoids and perfume materials*; *toilet*, *polishing and cleansing preparations*. Other main importing regions include the European Union (EU), Hong Kong, etc.

Generally, Macao's main importing regions are also the destinations of Macao's exported commodities. At the same period, mainland China also receives the largest proportion of energy embodied in exports from Macao. However, the embodied energy in Macao's exported commodities decreased from 1.59E+7 GJ in 2000 to 3.07E+6 GJ in 2011. The decrease primarily is attributed to the decline of Macao's garment industry, which used to be the pillar of Macao's commodity export. Affected by the same reason, most of Macao's trade partners like France, the USA receives less and less energy embodied in Macao's exported commodities from Macao. Even though, one exception can be witnessed, embodied energy in commodities that Hong Kong receives from Macao increases from 1.01E+6 GJ in 2000 to 1.77E+6 GJ 2011, due to the growing export of *Raw hides*, *skins and leather* and *Tobacco and wine*.

Integrating the energy embodied in imports with that in exports, the net embodied energy transfers via commodity trade from other regions to Macao are obtained. As presented in Fig. 3,

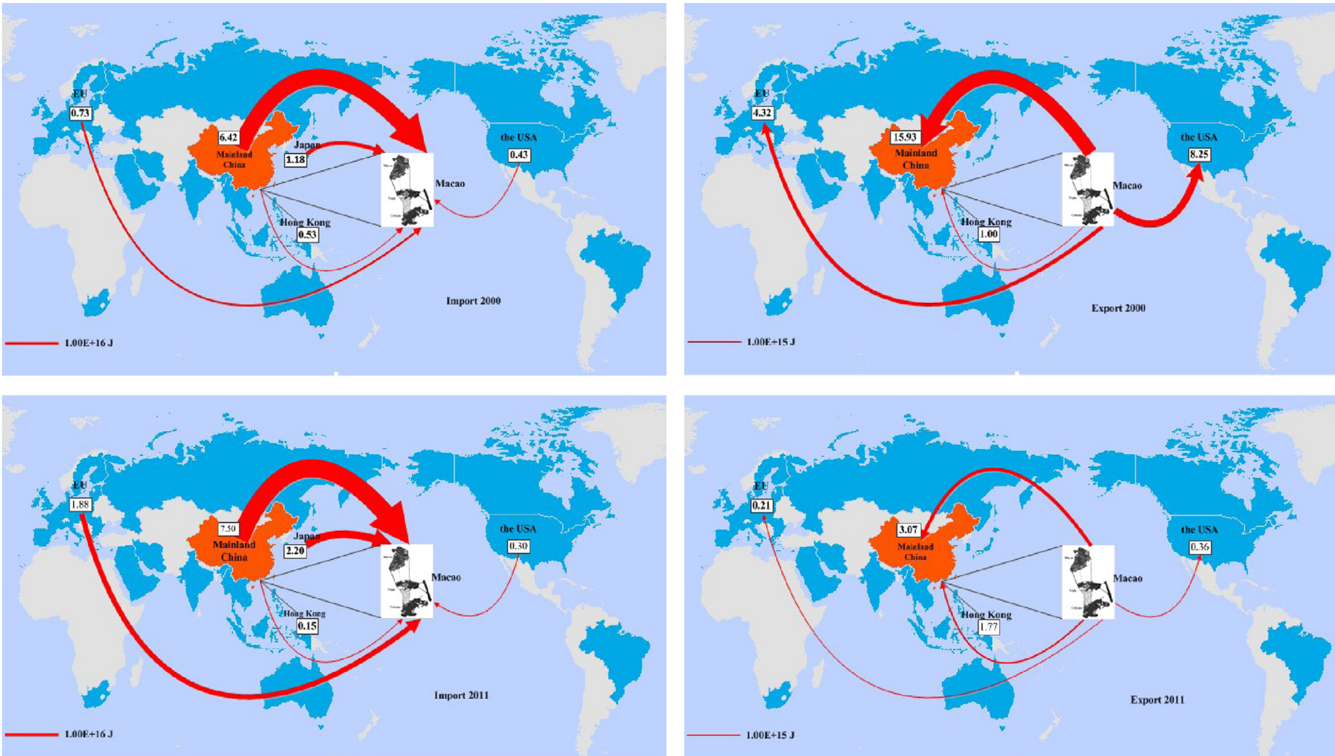


Fig. 3. Embodied energy connections between Macao and its major commodity trade partners.

mainland China maintains its position as the leading exporter and thanks to mainland China, Macao avoids 4.83E+7 GJ–7.19E+7 GJ direct energy inputs. This is followed by Japan, which is the second biggest embodied energy saver of Macao. It is also interesting to point out that there has been a change in the picture of the net embodied energy flows between Macao and its main commodity trade partners. In 2000, EU and the USA are the two regions which receive net embodied energy imports from Macao. When it comes to 2011, Hong Kong replaced EU and the USA as the only one region which has embodied energy surplus in trade with Macao.

3.2. *Energy embodied in service trade*[2]

3.2.1. *Energy embodied in imported services*

Fig. 4 depicts the Macao's consumption of embodied energy in imported services, which has shown dramatic growth in the period concerned. In 2011 energy embodied in imports of services amounts to 3.76E+7 GJ, which is about as 7 folds large as that in 2000. However, fluctuation can also be witnessed in this period, after 8 consecutive years' fast growth, Macao's consumption of embodied energy in imported services decreased in 2009 due to the influence of the world's financial crisis. Shown in Fig. A2, embodied energy of other services is contributes most to the growth of imported services, followed by household final consumption expenditure abroad which is the biggest individual contributor of imported services, transport services and government expenditure abroad.

3.2.2. *Energy embodied in exported services*

The services exported to non-Macao residents are classified as gaming, accommodation, industrial services, transport services, financial and insurance services, postal and telecom services and others. The energy embodied in exported services keeps the growing trend in the period concerned, increasing from 1.65E+7 GJ in 2000 to 8.94E+7 GJ in 2011. As demonstrated in Fig. 5, energy embodied in exported gaming service gradually dominates the total exported energy embodied in services. When it comes to the year of 2011, gaming service contributes almost 70% of the total (Fig. A3). Following next are the accommodation related services exports and transport services. Unlike the exported energy embodied in gaming service's consistent upward trend, the trends of energy embodied in other exported services vary in the same period.

3.3. *Energy embodied in external trade and embodied energy intensity*

Conventional analysis on external trade summarized in Fig. 6 is the energy embodied in external trade in the period of 2000~2011. In general, the amounts of energy embodied in both exports and imports experience from 2000 to 2011, although ups and downs can be seen in the same period. Energy embodied in imports increases from 1.08E+8 GJ in 2000 to 1.93E+8 GJ in 2011, and that of exports grows from 4.65E+7 GJ to 9.53E+7 GJ in the same period. It is obvious that energy embodied in the imported goods including energy products far exceeds the energy embodied in imported services. With respect to embodied energy in exports, a rapid change can be seen in the structure of exports. The amount of embodied energy in exported services gradually surpasses that of exported commodities and finally dominates the total exports. The large value of embodied energy of exports indicates that part of Macao's energy consumption is caused by non-Macao residents.

As the energy products consumed by Macao are all imported, the profile of Macao's energy trade can also be considered as the full picture Macao's total energy consumption. With the combination of direct energy input and indirect energy, the overall energy consumption of Macao over 2000~2011 is depicted in Fig. 7.

[2] Unlike the commodity trade, the data on service trade between Macao and its trade partners are unknown. As a result, the connections between Macao and its service trade partners not available in the current study.

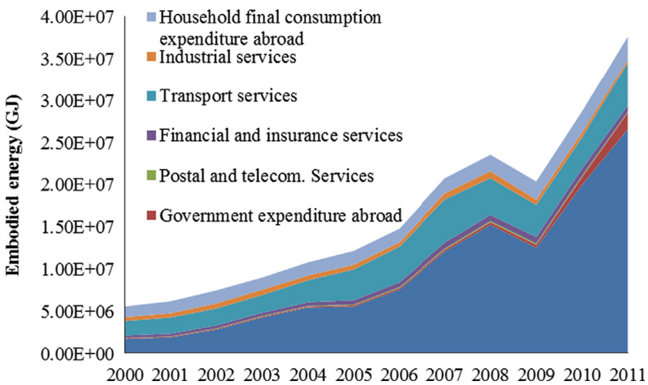


Fig. 4. Energy embodied in imported services.

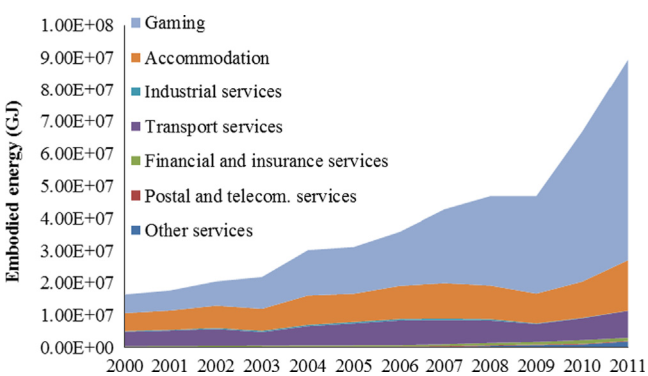


Fig. 5. Energy embodied in exported services.

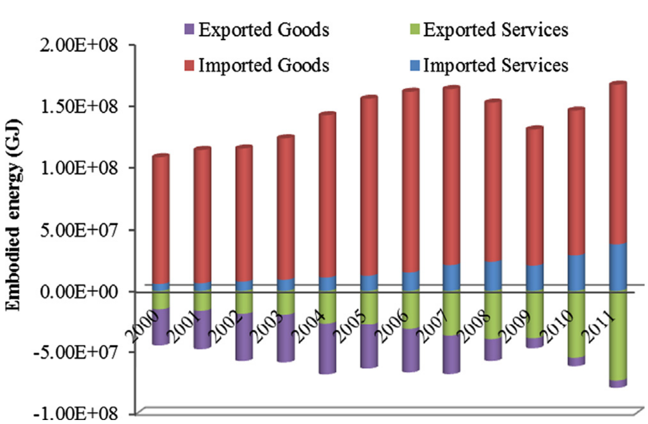


Fig. 6. Energy embodied in external trade.

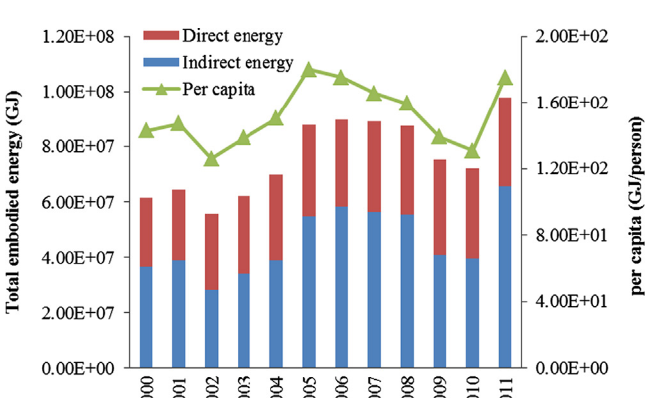


Fig. 7. Total embodied energy and per capita energy consumption.

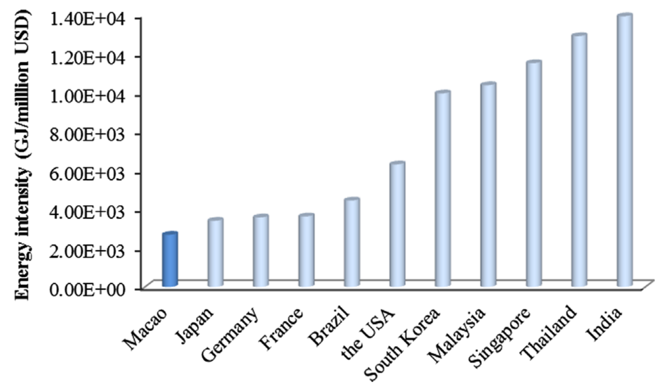


Fig. 8. Energy intensity of different countries/regions in 2011.
Data Source: [65].

Although the embodied energy required by Macao experienced fluctuation, generally the total energy consumption of Macao increased from 2000 to 2011. In 2000 the embodied energy consumption of Macao amounted to 6.31E+7 GJ, and 11 years later, the energy requirement of Macao reached 8.75E+7 GJ in 2011. Consumption of indirect energy has the dominant effect on Macao's overall embodied energy consumption, indicating that Macao avoids the majority of its direct energy consumption through external trade.

The trend of per capita embodied energy consumption shows an inverted U shape, very similar to that of total embodied energy consumption. In contrast to the increasing total energy consumption, Macao's per capita embodied energy consumption experienced apparent decrease in the same period (Fig. 7).

The embodied energy intensity (per unit GDP energy consumption) dropped sharply from 1.02E+4 GJ/million USD to 2.40E+3 GJ/million USD. The dramatic change can be attributed to Macao's service dominated economy and the fact that the growth rate of Macao's economy outpaced that of energy consumption. From 2000 to 2011, Macao's GDP has increased by about 6 times, while embodied energy consumption only increases by about 50%. Fig. 8 compares Macao's energy intensities with that of different economies in 2011. It can be seen that Macao's energy intensity is comparable to that of developed countries such as Japan and Germany, but much lower than that of developing countries like Thailand and India. Macao's low energy intensity can mainly attribute to its dominant industry–gaming industry, which is characterized as relatively low energy demand but high economic output.

4. Discussion

The results have shown that Macao has avoided large amount of direct energy consumption through external trade. The growing embodied energy deficit indicates that Macao is occupying more and more resources outside its borders to meet its own consumption. The large amount of embodied energy not only reflects Macao's heavy reliance on other regions but also releases a signal which shows Macao is moving away from sustainability in regional and global perspectives. Macao transferred high energy-intensive industries such as electricity generation to mainland China through trade, which not only induced consumption of large amount of energy, but also caused GHG emissions and air pollution. It is clear that although Macao claimed that it has devoted large efforts to reduce energy consumption [66], this goal is achieved by the cost of causing large indirect energy in other places.

It is important to note that two factors have impacts on Macao's embodied energy trade in this period. One is Macao's economic

strategy adjustment. For a long time before Macao returned to China, its economy relied on both tertiary industries like gambling and secondary industries like textile and toy-making. After 1999, Macao fosters an economic model built on tertiary industries characterized as gambling related tourism rather than the secondary industry, which results in the remarkable changes of Macao's embodied energy structure. After 2002 when Macao's government started to reform the gambling, Macao's gaming industry and related tourism entered a rapid development track while the traditional pillar such as the industry-textile gradually declined. As a consequence, the amount of energy embodied in Macao's exported services began to fast grow and finally surpassed that of exported commodities. The other significant factor is that the world's economy crisis happened in 2008. As presented in Fig. 6, energy embodied in both exports and imports experienced obvious growth. Influenced by the world's economy crisis, the energy embodied in both imports and exports witness a decrease.

The results have also shown that Macao's embodied energy consumption is over 2 times as that of direct energy consumption, which verifies that the ignorance of indirect energy would cause huge uncertainty and misunderstanding of Macao's energy consumption. Moreover, since 2008, Macao has been admitted to be a member of Kyoto Protocol, which means Macao should take the responsibility to reduce GHG emissions as well as energy conservation. To reduce the contribution of Macao's energy use to global GHG emissions, reductions on direct energy consumption alone are far from enough. The consumption of large amounts of commodities by Macao has an indirect effect on regions outside Macao where energy extraction and combustion, manufacturing, transportation and other production processing take place. And somehow, compared to the direct energy consumption, the indirect energy embodied in the imported goods is much larger and even outweighs the impact of direct energy use. Therefore, on a systematic or global scale, Macao should be responsible for the environmental change induced by its consumption, no matter where the change happens.

To alleviate the double pressure of energy shortage and GHG emissions reduction, comprehensive and effective measures should be implemented in Macao. Generally, there are two basic methods to ease Macao's energy shortage: broaden the local energy sources and reduce the energy consumption. Due to the absence of indigenous fossil energy resources, Macao can turn its eyesight towards renewable energy. It is reported Macao has relatively abundant solar energy [12], which means there is potential solar application in Macao. However, limited by the extremely small and overpopulated territory, large scale solar power plants are not suitable for Macao. As a consequence, Macao can choose solar-roof technology as the most effective way to utilize solar energy.

To encourage solar energy application, Macao should formulate comprehensive measures including legal, administrative and economic means. As Macao disclosed its intention for solar energy utilization, legislation on solar power is expected in 2014 [67]. The news was released by Arnaldo Santos, the director of Macao's Office for the Development of the Energy Sector at a conference titled “Solar Power Generates Greener Community”. It is said that the would-be law will include technical requirements for solar power. Apart from legislation to regulate the solar power installations, the formation of incentives is also important to promote solar power. Feed-in tariffs (FITs) has been proven as governments' most effective incentive program for renewable energy, solar energy is no exception. As a matter of fact, half of world's solar PV installations can be attributed to FITs [68]. Additional supports such as tax incentives can be given to commercial investors for solar power. The economic measures are likely to play key role in solar power development. As the cost of solar power is still several times higher than that of gas-fired electricity [69], the increase of electricity price may hinder the solar power development in Macao. Luckily, Macao government is rich enough to set a reasonable price, which means the increased price will not transfer to local residents.

To ease the heavy reliance on energy import, Macao starts promoting solar power, at the same time; the Macao government has focused on improving energy efficiency. The concept of eco-efficiency aiming to minimize energy consumption and reduce wastage was introduced by the Macao government to achieve the highest efficiency. The government is suggested to be dedicated to technical and structural changes. For instance, intellectual building which helps save energy use is a good choice as buildings are one of the main energy consumers in Macao [70]. New products which require less energy and switching fuels to renewable energy can be developed and promotional activities on how to increase energy effectiveness should also be promoted. Meanwhile, the government can give economic incentives to firms or communities who achieve greater efficiency by optimizing the use of energy, materials and community resources.

Additionally, the policy makers should propose clear and appropriate energy plans under local reality. For instance, Macao can use its advantage of high degree of autonomy to introduce legislation to promote energy – saving and sustainable development of the whole society. Regulations like energy management and reducing embodied energy intensity should be implemented as basic policies for the special region government. Secondly, Macao can follow the example of mainland China to make its own five-year plan development plan which integrates the economy with energy requirement. Last but not the least, the government can also make efforts to promote local residents' willingness to save energy, as residents of Macao do not have enough professional knowledge or scientific understanding on energy conservation and GHG emissions [71]. Fortunately, the government has already noticed that problem and started to pay more attention to public education and organized some activates to promote the notion of energy conservation, which is anticipated to ease this problem in the near future.

5. Conclusion

This is the first review study which assesses Macao's embodied energy in trade and highlights the significance of the indirect energy induced by Macao. Our results reveal several interesting findings such as the trend of Macao's energy embodied in trade, overall embodied energy consumption and energy intensities, Macao's main trade partners, the structure of Macao's embodied energy consumption after it seceded from the control of Portugal.

Generally, energy embodied both in imports and exports experiences considerable growth, with imports increasing from 1.08E+8 GJ to 1.93E+8 GJ and that of exports growing from 4.65E+7 GJ to 9.53E+7 GJ. As far as the commodity trade partners concerned, mainland China plays a central role in both Macao's imports and exports. Macao's embodied energy consumption witnessed growth from 6.31E+7 GJ in 2000 to 8.75E+7 GJ in 2011. On the contrary, the embodied energy intensity fell from 1.02E+4 GJ/million USD to 2.40E+3 GJ/million USD in the same period. As a typical heterotrophic city, Macao avoided large amounts of direct energy consumption through external trade, which resulted in the phenomenon that the amount of indirect energy requirement of Macao is much more than that of direct energy requirement over the 12 years. It validates the notion that direct assessment is far from sufficient to draw a full picture of Macao's tertiary industry dominated economy. As a result, to optimize the use of energy in order to reduce its impact on global

environment, the decision makers need to formulate an energy policy under the perspective of embodied analysis.

To sustain its escalating socio-economic development, Macao will be inevitably confronted with great pressure caused by increasing energy requirement such as energy shortage and environmental protection, due to the fact that Macao extremely lacks in indigenous natural resources and the ecosystem of Macao is already fragile. Under this circumstance, it is crucial for Macao to take actions to tackle with the energy related issues. Multiple measures are suggested to be implemented to cope with these problems. For instance, Macao can introduce energy conservation laws, make development plans that aim to improve energy efficiency and utilize local renewable energy resources, and raising the local residents' awareness to save energy through public education.

Acknowledgment

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Appendix A

See Figs. A1-A3 and Tables A1-A4.

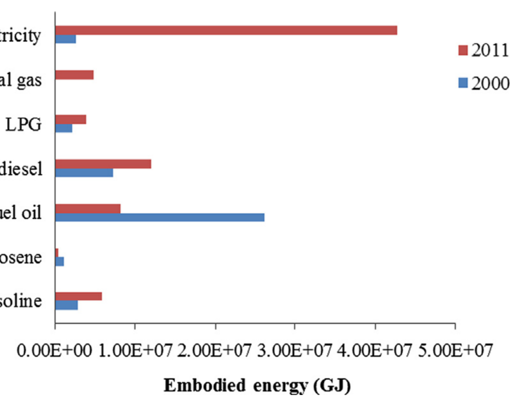


Fig. A1. Comparison of embodied energy of energy products in 2000 and 2011.

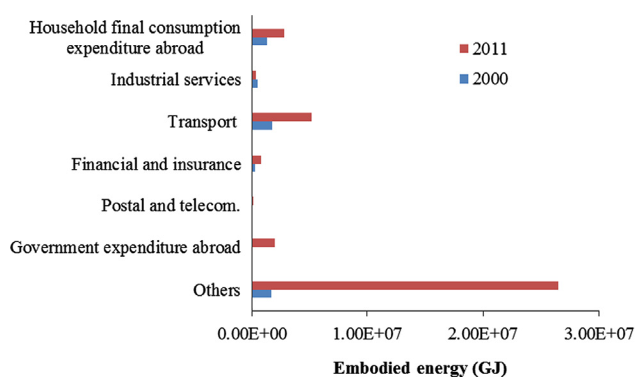


Fig. A2. Comparison of embodied energy of imported services in 2000 and 2011.

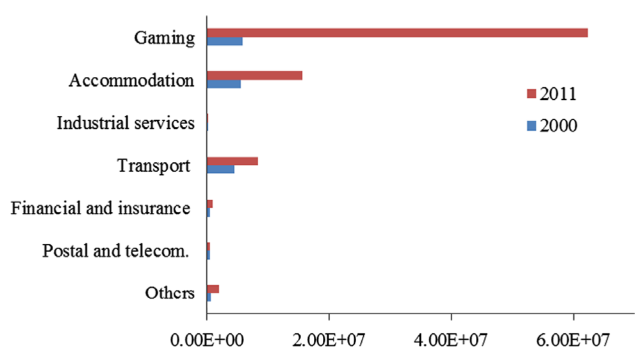


Fig. A3. Comparison of embodied energy of exported services in 2000 and 2011.

Table A1
Inventory of imports.

Code	Item
1	Live animals other than animals of division 3
2	Meat and meat products
3	Fish (not marine mammals), crustaceans, molluscs and aquatic invertebrates, and preparations thereof
4	Cereals and cereal preparations
5	Vegetables and fruit
6	Sugars, sugar preparations and honey
7	Coffee, tea, cocoa, spices and manufactures thereof
8	Feeding stuff for animals (not including unmilled cereals)
9	Beverages
10	Dairy products and birds' eggs
11	Miscellaneous edible products preparations
12	Tobacco and tobacco manufactures
13	Plastics in primary forms
14	Rubber manufactures, n.e.s.
15	Paper, paperboard and articles of paper pulp, of paper or of paperboard
16	Textile yarn, fabrics, made-up articles, n.e.s., and related products
17	Inorganic chemicals
18	Non-metallic mineral manufactures, n.e.s.
19	Iron and steel
20	Non-ferrous metals
21	Metal products, n.e.s.
22	Fixed vegetable fats and oils, crude, refined or fractionated
23	Essential oils and resinoids and perfume materials; toilet, polishing and cleansing preparations
24	Medicinal and pharmaceutical products
25	General industrial machinery and equipment, n.e.s., and machine parts, n.e.s.
26	Power-generating machinery and equipment
27	Machinery specialized for particular industries
28	Office machines and automatic data-processing machines
29	Telecommunications and sound recording and reproducing apparatus and equipment
30	Electrical machinery, apparatus and appliances, n.e.s., and electrical parts thereof
31	Road vehicles (including air-cushion vehicles)
32	Other transport equipment
33	Prefabricated buildings; sanitary, plumbing, heating and lighting fixtures and fittings, n.e.s.
34	Articles of apparel and clothing accessories
35	Travel commodities, handbags and similar containers
36	Footwear
37	Photographic apparatus, equipment and supplies and optical commodities, n.e.s.; clocks and watches
38	Professional, scientific and controlling instruments and apparatus, n.e.s.
39	Miscellaneous products, n.e.s.
40	Raw water
41	Gasoline
42	Kerosene
43	Fuel oil
44	Gas oil and diesel
45	Liquefied Petroleum Gas
46	Natural gas
47	Electricity
48	Government expenditure abroad
49	Postal and telecom services
50	Financial and insurance services
51	Transport services
52	Industrial services
53	Household final consumption expenditure abroad
54	Other services

Note: "n.e.s." means not elsewhere specified.

Table A2
Inventory of exports.

Code	Item
1	Garments
2	Textile fabrics
3	Textile yarn and thread
4	Textile raw materials
5	Textile made-up articles and related products
6	Feathers, down and articles thereof
7	Toys
8	Raw hides, skins and leather
9	Articles of apparel, clothing accessories and other articles of leather or fur skins
10	Optical instruments
11	Footwear

Table A2 (*continued*)

Code	Item
12	Travel commodities, handbags and related products
13	Machines and mechanical appliances; parts and accessories
14	Radios, televisions, image and sound recorders and reproducers, etc.; parts and accessories
15	Electrical and electronic components and articles for electro-technical use
16	Furniture, including frames, cases, suitcases and similar articles
17	Clocks and watches
18	Copper and articles thereof
19	Tobacco and wine
20	Jewelry
21	Postal and telecom services
22	Financial and insurance services
23	Transport services
24	Industrial services
25	Accommodation
26	Other services

Table A3
Embodied energy of imported commodities (Unit: GJ).

Item	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
1	2.44E+05	2.72E+05	3.29E+05	3.70E+05	3.71E+05	3.45E+05	3.29E+05	2.65E+05	2.20E+05	2.88E+05	2.66E+05	3.52E+05
2	7.88E+04	9.39E+04	1.25E+05	1.50E+05	1.95E+05	2.21E+05	2.45E+05	3.40E+05	4.65E+05	5.23E+05	5.97E+05	7.11E+05
3	1.10E+05	1.41E+05	1.94E+05	2.64E+05	2.65E+05	3.02E+05	3.15E+05	3.82E+05	4.14E+05	4.60E+05	5.21E+05	5.77E+05
4	1.14E+05	1.20E+05	1.36E+05	1.65E+05	2.04E+05	2.61E+05	2.89E+05	3.47E+05	3.81E+05	4.03E+05	4.47E+05	4.95E+05
5	3.20E+05	3.48E+05	3.90E+05	4.54E+05	6.10E+05	7.06E+05	6.87E+05	8.64E+05	7.68E+05	7.32E+05	7.93E+05	8.77E+05
6	4.63E+04	5.29E+04	5.50E+04	6.61E+04	7.71E+04	9.59E+04	1.09E+05	1.24E+05	1.15E+05	1.13E+05	1.27E+05	1.43E+05
7	5.55E+04	5.84E+04	7.25E+04	8.23E+04	1.00E+05	1.26E+05	1.56E+05	2.02E+05	2.08E+05	2.07E+05	2.04E+05	2.68E+05
8	1.95E+04	2.09E+04	2.46E+04	2.74E+04	2.94E+04	3.24E+04	2.70E+04	2.82E+04	3.19E+04	3.24E+04	3.59E+04	3.76E+04
9	8.11E+05	1.46E+06	1.45E+06	1.45E+06	1.60E+06	1.76E+06	1.91E+06	2.02E+06	1.94E+06	2.37E+06	2.99E+06	3.94E+06
10	1.26E+05	1.41E+05	1.71E+05	1.96E+05	2.25E+05	2.86E+05	3.25E+05	3.92E+05	4.33E+05	5.19E+05	6.41E+05	8.54E+05
11	1.12E+05	1.15E+05	1.44E+05	1.81E+05	2.52E+05	3.24E+05	3.53E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	3.57E+05	4.18E+05	4.30E+05	5.81E+05	7.18E+05	8.01E+05	7.27E+05	7.84E+05	7.22E+05	6.57E+05	6.71E+05	8.57E+05
13	1.02E+05	6.50E+04	5.48E+04	6.88E+04	1.67E+05	3.14E+05	3.69E+05	3.73E+05	2.64E+05	1.30E+05	1.50E+05	1.43E+05
14	1.41E+05	1.05E+05	1.42E+05	1.26E+05	1.26E+05	1.08E+05	1.16E+05	9.63E+04	7.62E+04	7.69E+04	8.43E+04	9.06E+04
15	3.18E+05	4.52E+05	4.95E+05	5.40E+05	5.17E+05	4.99E+05	6.02E+05	7.00E+05	6.39E+05	5.83E+05	6.18E+05	6.63E+05
16	4.55E+07	4.74E+07	4.40E+07	4.70E+07	5.20E+07	4.91E+07	4.10E+07	2.83E+07	1.45E+07	5.50E+06	4.48E+06	2.91E+06
17	2.60E+04	2.82E+04	1.97E+04	6.21E+04	5.80E+04	1.26E+05	1.21E+05	2.28E+05	1.61E+05	1.49E+05	1.52E+05	1.57E+05
18	3.28E+05	3.22E+05	3.83E+05	5.94E+05	7.38E+05	1.53E+06	2.85E+06	2.61E+06	2.06E+06	1.22E+06	9.47E+05	1.19E+06
19	4.60E+05	5.32E+05	5.86E+05	1.43E+06	2.43E+06	7.52E+06	9.77E+06	1.09E+07	8.39E+06	1.79E+06	2.13E+06	4.30E+06
20	8.35E+04	4.08E+04	6.28E+04	9.13E+04	2.02E+05	2.47E+05	3.99E+05	3.86E+05	3.79E+05	1.76E+05	2.75E+05	2.76E+05
21	9.27E+04	7.32E+04	8.52E+04	9.66E+04	1.57E+05	1.82E+05	2.89E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
22	7.67E+04	6.77E+04	7.96E+04	8.94E+04	8.99E+04	7.55E+04	7.02E+04	9.04E+04	1.04E+05	1.21E+05	1.13E+05	1.15E+05
23	9.56E+05	1.13E+06	1.16E+06	1.48E+06	2.07E+06	1.98E+06	1.83E+06	2.20E+06	2.20E+06	2.81E+06	3.05E+06	3.25E+06
24	1.25E+05	1.06E+05	1.10E+05	1.23E+05	1.46E+05	1.73E+05	2.08E+05	2.47E+05	2.72E+05	3.59E+05	4.51E+05	5.27E+05
25	2.00E+05	2.04E+05	2.33E+05	2.91E+05	4.25E+05	5.87E+05	6.51E+05	8.38E+05	8.36E+05	3.86E+05	3.90E+05	3.23E+05
26	3.44E+04	2.56E+05	2.30E+05	1.03E+05	3.32E+05	4.05E+05	5.13E+05	8.13E+05	1.43E+05	1.46E+05	1.15E+05	1.02E+05
27	1.17E+05	7.89E+04	8.13E+04	9.48E+04	3.30E+05	4.07E+05	2.61E+05	3.18E+05	2.24E+05	1.51E+05	1.44E+05	1.42E+05
28	1.71E+05	2.64E+05	1.22E+05	1.14E+06	4.23E+05	2.24E+06	2.91E+06	3.86E+06	2.55E+06	1.60E+06	2.10E+06	3.50E+06
29	6.27E+05	1.26E+06	8.36E+05	1.36E+06	1.36E+06	2.88E+06	3.34E+06	4.28E+06	4.12E+06	4.11E+06	5.42E+06	8.00E+06
30	1.77E+06	9.77E+05	8.22E+05	6.69E+05	1.43E+06	1.24E+06	2.26E+06	2.64E+06	2.81E+06	1.92E+06	1.70E+06	2.15E+06
31	3.82E+05	4.71E+05	4.99E+05	7.04E+05	8.80E+05	1.08E+06	1.04E+06	1.30E+06	1.16E+06	9.91E+05	1.54E+06	2.05E+06
32	2.64E+05	1.65E+05	2.54E+05	1.97E+05	1.39E+05	1.67E+05	2.34E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
33	2.17E+04	4.55E+04	5.63E+04	3.85E+04	6.74E+04	8.85E+04	1.52E+05	2.49E+05	2.36E+05	1.36E+05	8.89E+04	1.79E+05
34	4.28E+06	5.25E+06	5.93E+06	5.91E+06	7.98E+06	8.25E+06	8.34E+06	8.28E+06	5.99E+06	2.33E+06	2.74E+06	3.38E+06
35	1.32E+04	1.41E+04	2.68E+04	4.73E+04	7.04E+04	1.02E+05	1.77E+05	3.36E+05	6.59E+05	9.82E+05	1.67E+06	3.39E+06
36	7.83E+05	1.14E+06	9.18E+05	8.06E+05	1.51E+06	4.43E+05	9.14E+05	9.85E+05	7.69E+05	7.55E+05	1.00E+06	1.43E+06
37	2.46E+04	3.50E+04	9.71E+04	1.67E+05	2.38E+05	3.12E+05	5.44E+05	9.15E+05	1.52E+06	1.80E+06	2.54E+06	3.43E+06
38	3.53E+04	5.34E+04	5.56E+04	7.90E+04	1.02E+05	1.39E+05	1.14E+05	1.95E+05	1.86E+05	2.06E+05	2.10E+05	2.17E+05
39	5.38E+05	5.94E+05	7.66E+05	9.03E+05	1.49E+06	1.63E+06	2.12E+06	9.31E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
40	2.32E+05	2.16E+05	2.16E+05	2.25E+05	2.35E+05	2.35E+05	2.67E+05	3.21E+05	3.27E+05	3.39E+05	3.02E+05	3.14E+05
Total	6.01E+07	6.46E+07	6.19E+07	6.84E+07	8.04E+07	8.73E+07	8.70E+07	7.81E+07	5.63E+07	3.51E+07	3.97E+07	5.13E+07

Table A4
Embodied energy of exported commodities (Unit: GJ).

Item	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
1	1.17E+07	1.09E+07	1.12E+07	1.27E+07	1.35E+07	1.18E+07	1.17E+07	1.10E+07	7.49E+06	1.94E+06	1.21E+06	9.17E+05
2	1.06E+07	1.25E+07	1.72E+07	1.68E+07	1.74E+07	1.59E+07	1.47E+07	1.14E+07	4.57E+06	2.06E+06	1.71E+06	1.26E+06
3	3.57E+06	4.58E+06	5.83E+06	4.37E+06	4.72E+06	3.99E+06	3.81E+06	2.70E+06	1.44E+06	9.04E+05	6.88E+05	5.42E+05

Table A4 (*continued*)

Item	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
4	1.21E+06	1.40E+06	2.19E+06	2.65E+06	1.28E+06	2.19E+05	3.50E+04	2.86E+04	1.94E+04	0.00E+00	0.00E+00	2.55E+04
5	3.45E+05	3.75E+05	6.27E+05	6.59E+05	6.88E+05	7.50E+05	8.66E+05	7.11E+05	3.68E+05	1.66E+05	0.00E+00	1.26E+05
6	9.07E+03	6.54E+03	4.42E+03	4.39E+03	4.33E+03	7.18E+03	2.75E+03	1.79E+03	1.67E+03	1.68E+03	0.00E+00	0.00E+00
7	1.03E+04	1.08E+04	7.63E+03	1.97E+04	1.35E+04	1.56E+04	2.28E+04	1.22E+04	1.35E+04	8.62E+03	8.27E+03	5.34E+03
8	6.99E+04	6.42E+04	6.69E+04	7.43E+04	5.56E+04	4.21E+04	3.50E+04	4.58E+04	4.47E+04	1.55E+04	8.87E+03	1.79E+04
9	1.47E+03	3.07E+03	4.58E+03	4.55E+03	4.49E+03	5.70E+03	1.13E+04	6.28E+03	9.82E+03	4.56E+04	2.84E+04	1.60E+04
10	2.61E+03	2.73E+03	3.62E+03	7.19E+03	2.57E+04	1.93E+04	3.26E+04	3.39E+04	3.49E+04	2.26E+04	3.85E+04	4.37E+04
11	8.09E+05	8.58E+05	8.93E+05	9.91E+05	1.09E+06	1.06E+05	4.96E+05	4.84E+05	1.54E+05	8.53E+04	6.61E+04	8.01E+04
12	2.70E+04	1.15E+04	9.37E+03	4.14E+03	4.08E+03	5.79E+03	6.41E+03	1.40E+04	4.10E+04	5.88E+04	5.72E+04	7.29E+04
13	1.02E+06	6.30E+05	6.31E+05	7.46E+05	1.39E+06	1.57E+06	1.66E+06	2.47E+06	1.15E+06	5.61E+05	3.99E+05	4.69E+05
14	1.18E+05	7.01E+04	5.77E+04	3.41E+04	3.26E+04	3.95E+04	3.69E+04	7.37E+04	9.59E+04	1.01E+05	1.10E+05	5.29E+04
15	3.12E+05	2.02E+05	3.00E+05	3.11E+05	4.14E+05	1.80E+05	2.02E+05	3.48E+05	3.59E+05	3.22E+05	3.37E+05	3.78E+05
16	1.42E+04	8.68E+03	9.86E+03	7.35E+03	8.46E+03	9.13E+03	9.76E+03	1.46E+04	2.18E+04	1.19E+04	1.24E+04	1.04E+04
17	0.00E+00	1.00E+03	1.99E+03	9.91E+02	1.95E+03	1.75E+04	7.10E+04	4.34E+04	7.29E+04	2.51E+05	2.71E+05	1.85E+05
18	2.01E+03	2.10E+03	0.00E+00	0.00E+00	8.27E+05	9.34E+05	1.11E+06	1.16E+06	8.63E+05	6.07E+05	8.81E+05	8.34E+05
19	1.96E+05	2.43E+05	0.00E+00	0.00E+00	2.92E+05	3.54E+05	3.86E+05	3.47E+05	4.34E+05	3.85E+05	5.47E+05	7.03E+05
20	2.39E+04	0.00E+00	0.00E+00	0.00E+00	1.77E+05	2.48E+05	6.21E+04	3.34E+05	5.43E+05	6.05E+05	4.72E+05	1.57E+05
Total	3.00E+07	3.20E+07	3.90E+07	3.94E+07	4.19E+07	3.62E+07	3.53E+07	3.12E+07	1.77E+07	8.15E+06	6.85E+06	5.89E+06

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